REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 17 November 1995	3. REPORT TYPE AND DATES COVERED Final Technical 6/30/93 - 6/30/95

4. TITLE AND SUBTITLE

STUDY OF FLUID DYNAMICS WITH INTEGRATED MICRO SENSORS

5. FUNDING NUMBERS

G-F49620-92-J-0531

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AFOSR-TR
96-0030

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AFOSR/NA
110 Duncan Avenue, Suite E115
Bolling AFB, DC 20332-0001

NA

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

F49620-92-J-0531

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for publice release; distribution is unlimited.

12b. DISTRIBUTION CODE

19960202 019

13. ABSTRACT (Maximum 200 words)

The drastic size reduction in the micromachine field results in the breakdown of the scaling laws used in traditional engineering fields because the large length scale change is significant enough such that the equations governing the momentum and energy balances need to be re-examined. For example, the gas flow in a micromachine might not be considered as continuum anymore. In addition, the inter-link among these fields becomes important in micron scales such that the surface physics and chemistry may significantly affect the boundary conditions in fluid mechanics. In this study, a very simple flow configuration, flow through a straight channel, was used to investigate the challenges in the micro world. While monatomic gas, helium, was used as the working medium, the mass flow rate and streamwise pressure distribution can be calculated from the Navier-Stokes equation with a slip flow boundary condition. However, the measured pressure distributions of polyatomic gases, e.g. oxygen, nitrogen and carbon dioxide, do not agree with the analytical results. It is surprising that these polyatomic gases have much lower Knudsen number than that of helium.

14. SUBJECT TERMS

MEMS, fluid science, micro sensor

15. NUMBER OF PAGES

14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited

NSN 7540-01-280-5500

DTIC QUALITY INSPECTED 1

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

Study of Fluid Dynamics with Integrated Micro Sensors
F49620-92-J-0531
6/30/1993 - 6/30/95

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GOAL

The goal of this project is to understand the flow physics inside a micro channel with a dimension close to the mean free path of gases.

Key Words: MEMS, fluid science, micro sensor

ABSTRACT

The drastic size reduction in the micromachine field results in the breakdown of the scaling laws used in traditional engineering fields because the large length scale change is significant enough such that the equations governing the momentum and energy balances need to be re-examined. For example, the gas flow in a micromachine might not be considered as continuum anymore. In addition, the inter-link among these fields becomes important in micron scales such that the surface physics and chemistry may significantly affect the boundary conditions in fluid mechanics. In this study, a very simple flow configuration, flow through a straight channel, was used to investigate the challenges in the micro world. While monatomic gas , helium, was used as the working medium, the mass flow rate and streamwise pressure distribution can be calculated from the Navier-

Stokes equation with a slip flow boundary condition. However, the measured pressure distributions of polyatomic gases, e.g. oxygen, nitrogen and carbon dioxide, do not agree with the analytical results. It is surprising that these polyatomic gases have much lower Knudsen number than that of helium.

INTRODUCTION

In micromachinery, fluid is frequently used to transport momentum and energy. Flow inside a micro tunnel is a basic flow configuration for this purpose. Many interesting scientific problems need to be understood in micro fluid dynamics. The pressure drop represents the cost to transport momentum and energy through this small passage, and it is an important design information. Pfahler et al (1991) used the bulk machining technique to fabricate micron size channels and measured the pressure difference between the inlet and the exit. The data was compared with the analytical results according to continuum assumption. Based on the measured pressure difference, the flow rate was higher than expected. In the case of gas flow, the Knudsen number which represents the ratio of the mean free path to the characteristic length of the flow can be large. Only a small number of gas molecules were present inside the tunnel. In this case, the well-known linear pressure distribution relation based on continuum assumption needs to be modified and the pressure distribution along the tunnel is a challenging problem for both experimentalists and theoreticians (Liu et al, 1993, Arkilic and Breuer, 1993, Beskok and Karniadakis 1993).

EXPERIMENTAL SETUP

Flow through a channel with dimensions of 4000μm × 40μm × 1.2μm is examined. The microchannel is manufactured by incorporating procedures originally designed to fabricated integrated circuit chips. The details of the channel can be found in the report in a companion grant to Caltech under the direction of Professor Yu-Chong Tai. Chip packaging is done to connect the micropressure transducers on the chip to a data acquisition system for pressure distribution measurements. A technique is devised to measure mass flow rate on the order of 10^{-12}kg/s from the outlet of the microchannel since conventional meters are inadequate.

The gas supply consists of a primary and settling tank. The primary tank holds the main supply, the gas being the highest purity available for research use. This tank is connected to a smaller settling tank via a pressure regulator. The regulator is used to control any sudden and unexpected surges from the primary supply. These bursts of gas can be large enough to damage the microchannel. The settling tank is used to allow the gas from the main supply to stabilize. A second regulator is connected to the settling tank to further prevent against any uncertainties in gas pressure. Initial tests without the second tank and regulator were short-lived as the micropressure sensors on the chip were damaged quite easily. The reason such an arduous effort is used to ensure against any sudden bursts is that the tanks are not designed to be used with microdevices. These bursts are not as

devastating to macrodevices as they are to miromachined chips. Keeping in mind that these gas tanks were designed with macrodevices in mind, more care must be used when adapting them to delicate instruments. Use of this system provides the inlet of the microchannel with a constant steady flow.

The filtration system consists of air filters which are used to clean the gas that will enter the microchannel. Even though only research grade (99.993% or higher in purity) is used, there is still a chance particles may clog the channel. To eliminate the possibility of such nuisances, two Solkatronic micropure membrane filters are used to prevent objects greater than $0.1\mu m$ and $0.02\mu m$ to pass into the microchannel. The possibility of blockage in the microchannel due to residue is then eliminated with these two safety precautions. The filters are also added insurance against any pressure surges if these are not handled well by the settling tank and two pressure regulators.

An analog to digital converter is used to measure the voltage readings from the pressure sensors on the chip. An IBM PC is used to receive the data from the 16-bit 100kHz ADC board, which consists of 32 channels. There are more channels than sensors on the microchannel chip, and thus only 13 channels are used. Collection is controlled by a program written in C. A series of calls to subroutines are used to perform an array of analog to digital conversions from the voltage readings coming from the National Instruments data acquisition board. The voltage readings are on order of 10^{-1} volts. The sampling rate is 1000 samples per second for all the sensors on the chip. Typically,

32,000 data points are collected at roughly half minute intervals and averaged for each inlet pressure. Standard deviation calculations are also done for each inlet pressure to make sure the values are not fluctuating. Typical deviations are on orders of 10^{-4}, which is quite reasonable considering the order of magnitude for the voltage readings.

RESULTS

Experimental trials were carried out with helium, nitrogen, oxygen, and carbon dioxide at varying inlet pressures. Pressure distribution and mass flow rate values were measured. The results are graphed with theoretical curves for comparison. Details can be found in the Master's thesis by Shih(1995). The results of helium and oxygen are summarized here.

Helium

Helium, a monatomic element, is first used to study flow through a microchannel. The gas is the lightest of the inert gases. Since its high Knudsen number falls into the transition regime ($Kn = 0.16$ at atmospheric conditions), helium was chosen to be the first test gas.

Since there is no theoretical analysis available for gas flow with Kn greater than 0.1, the slip boundary condition is used to see how the data points will compare with the slip solution. From Figure 1, the measured pressure distribution agrees well with the theoretical curve (solid lines). The data is representative of numerous measurements

taken. Similar agreements for helium gas are also reported by Liu (1994) and there is an agreement between both cases. The difference between the two lies in the length of the microchannel used in the analysis. For this case, 4000μm is used since the input pressure reading is taken at the second pressure sensor and ends at the twelfth one. The first and last sensors are neglected since end effects such as undeveloped flow can be unpredictable. Although the microchannel chip has thirteen pressure sensors, only eleven measurements are shown for each inlet pressure. This is adequate to show the nonlinear effect of pressure drop as a function of the streamwise position.
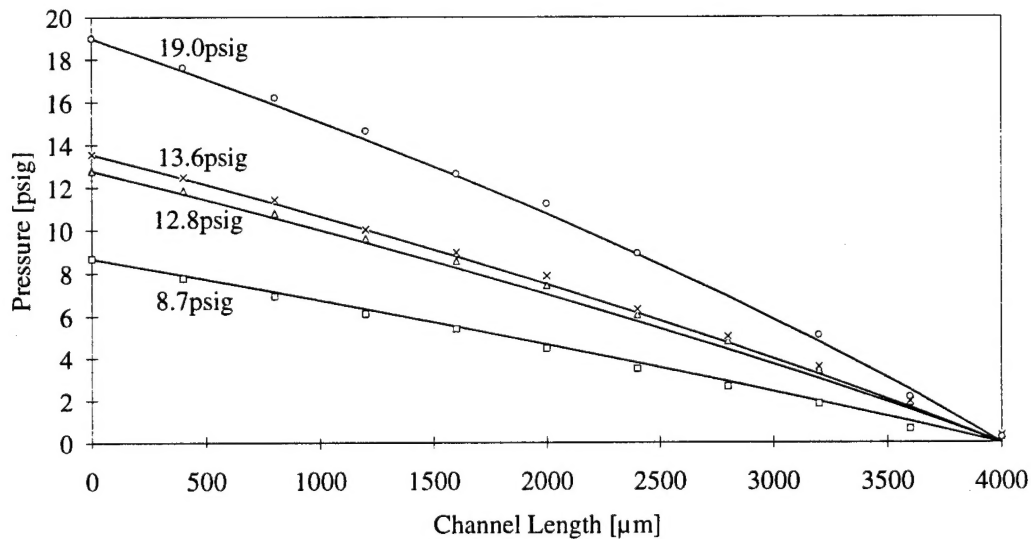

Figure 1. Pressure distribution for helium.

The theoretical mass flow rate curve along with the experimental values is seen in Figure 2. Using an averaged value of 1.1575 for the accommodation coefficient, the curve seems to predict the experimental values quite well, with the other 10% deviations overpredicting the data. The experimental coefficient is reasonable as diffuse reflection

coefficients ranging from 0.2 to 1.5 have been reported for various gases flowing over different surfaces. Unfortunately, data is unavailable for helium flowing over both silicon and nitride. To analyze whether or not the experimental value is reasonable, one must keep in mind that at $\alpha = 2$, flow is in continuum. Microchannel flow must be modeled with the slip boundary condition and thus since an accommodation value less than two is found, the value is reasonable. Liu (1994) uses a coefficient of about 1.2 to fit his data, which is only a 4% difference from this case. Both sets of data seem to fit well with roughly the same accommodation coefficient. To ensure the data taken is not fluctuating, experiments are done over a period of months. During each run, seven trials are done for each inlet pressure and the values are averaged into one mass flow rate data point. The no-slip solution (dotted line) is plotted for comparison, which is lower than the slip solution.
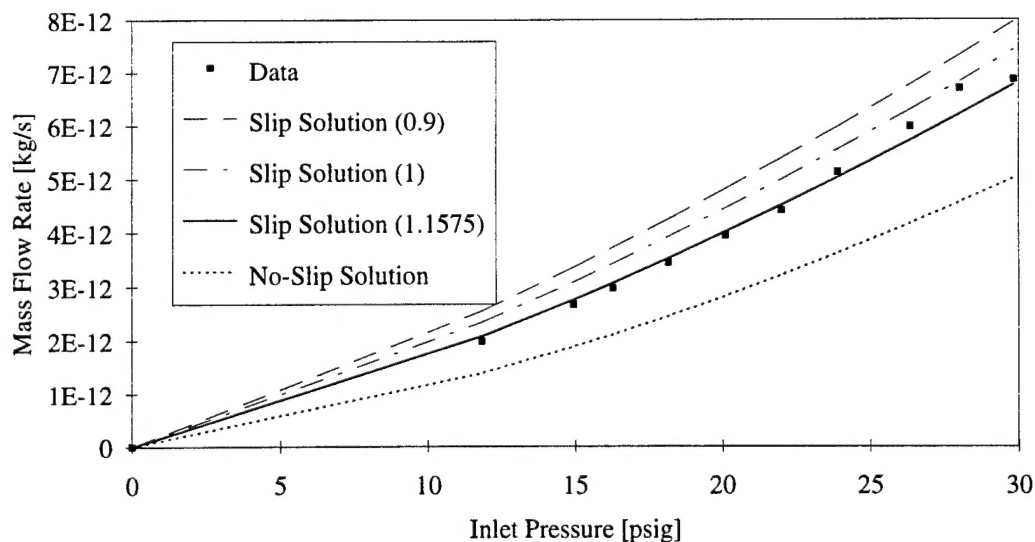
Figure 2. Mass flow rate distribution for helium.

Oxygen

Oxygen is a highly reactive gas which easily combines with most elements to form oxides. To study the deviation of diatomic gases from slip theory, oxygen is used as the second diatomic test gas. Knudsen is no greater than 0.06. The pressure distribution for oxygen is given in Figure 3. The predicted drop does not account for the sudden increase in pressure seen at $x = 800\mu m$. Also, the experimental data do not fit with theoretical curve. The deviation is more pronounced near the inlet and outlet of the channel.
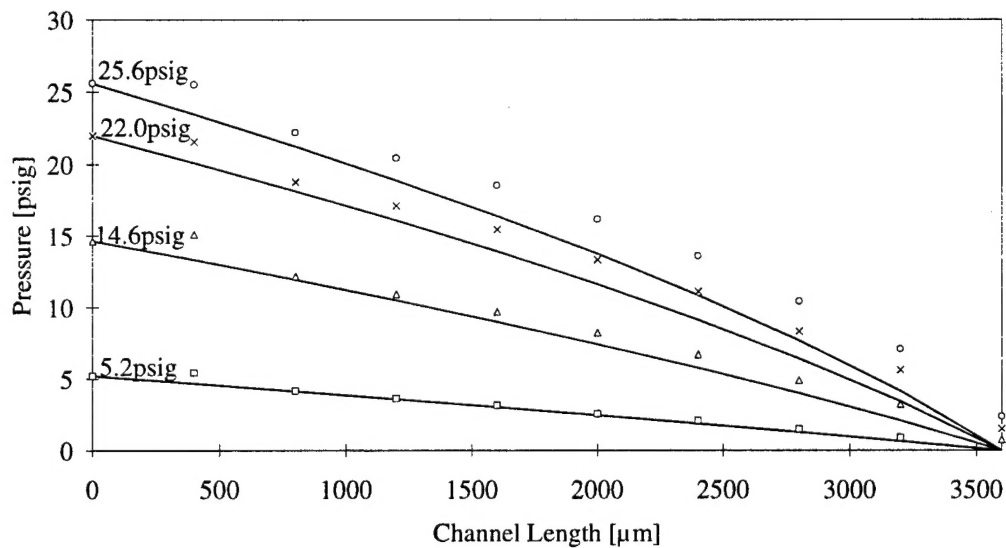

Figure 3. Oxygen pressure distribution.

The mass flow rate curve is shown in Figure 4. The graph is fitted with an averaged accommodation coefficient of 0.875, 10% deviations of this value underpredicting the data. The fit is reasonable up to a critical pressure. From the data, the theoretical predictions does not accurately predict oxygen's mass flow rate for inlet pressures greater than 25.0psig.
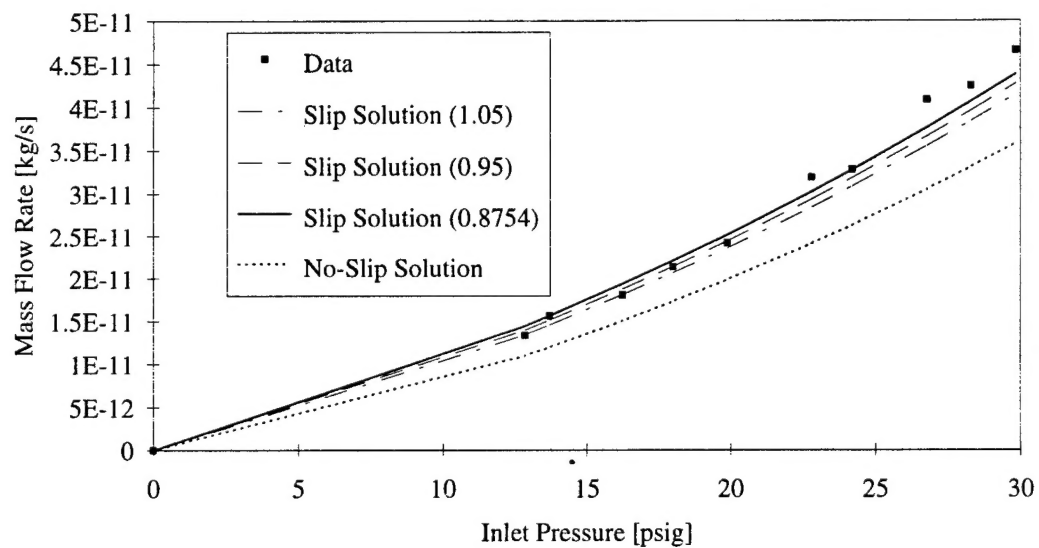
Figure 4. Mass flow rate distribution for oxygen.

CONCLUSION

A study of microchannel gas flow with helium, nitrogen, oxygen, and carbon dioxide gas has been presented. From the results, flow on the microscale cannot be predicted by conventional means. The data shows that the no-slip boundary condition cannot be used to predict flow in uniform microchannels. Intuition from conventional channel flow is irrelevant when dealing with flow through a structure only 1.2μm high. Modifying the boundary condition to account for slip, helium gas is predictable within reason. However, He gas does not seem to conform well when low inlet pressures are used since *Kn* signifies flow is in the transition regime. The results for the polyatomic gases (nitrogen, oxygen, and carbon dioxide) indicate significant deviations from theoretical predictions. For pressure distribution, areas of sudden pressure surges are seen near the channel's inlet for oxygen gas. For the most part, the rate of pressure drop is underpredicted with the slip condition. As for the mass flow rate, 25.0psig seems to be a critical pressure where the predicted curve deviates from the data any where from 7%-10%. Possible explanations for the discrepancy include channel wall deformation, undeveloped flow, and micro-surface interactions, all of which can influence flow behavior. In general, there seems to be little correlation between macroscale and microscale physics. The truth of the matter is that good intuition of microstructure behavior is only achieved through repetitive experimentation and thorough data analysis. A novel phenomena in microchannel flow along with possible explanations as to why conventional means are inadequate for flow predictions are presented. Future work will encompass microtomography techniques involving photosensor and x-ray penetration for

microchannel flow visualization, other more ingenious ways of pressure and flow rate

measurements, and the study of flows with even higher Knudsen numbers.

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PERSONALS SUPPORTED BY THIS GRANT

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AWARDS

Fellow of the American Physical Society, 1989

Fellow of American Institute of Aeronautics and Astronautics, 1994

UCLA-Allied Signal Faculty Research Award, 1994

KEYNOTE TALKS IN INTERNATIONAL CONFERENCES

"Flow Measurement and Control by MEMS"
The 6th International Symposium on Flow Modeling and Turbulence Measurements
Tallahassee, Florida, September 8-10, 1996.

"Interactive Control of Wall Structures by MEMS Based Transducers"
Sixth European Turbulence Conference
Lausanne, Switzerland, July 2-5, 1996.

"Flow Control by a Distributed Micro System"
Flow Control Workshop
Corsica, France, July 1-5, 1996.

"MEMS- An Innovative Approach to Transport Phenomena"
9th International Symposium on Transport Phenomena
Singapore, June, 25-28, 1996.

"Control of Streamwise Vortices in 2-D Channel Flow"
The 10th Turbulent Shear Flows
University Park, Pennsylvania, August 14-16, 1995.

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Hong Kong, September 5-9, 1994

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Twelfth U. S. National Congress of Applied Mechanics
Seattle, Washington, June 27 - July 1, 1994

"MEMS - A New Industrial Revolution"
Conference of Modern Mechanics
in commemoration of the 10th anniversary of the Institute of Applied Mechanics
Taipei, Taiwan, December 9-11, 1993

"Turbulence and Its Control"
International Symposium on Aerospace and Fluid Science,
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